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SELF-CONTAINED AUTOMATIC RECORDER OF THE DC JOSEPHSON CURRENT,(U)
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6 Self-Contained Automatic Recorder of The DC Josephson Current*

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Abstract

A circuit for the automatic recording of the dc Josephson current as a function of magnetic field or other variable has been designed and constructed. The apparatus requires no additional signal processing devices as have techniques for this measurement utilized in the past. Sensitivity to critical current amplitudes corresponding to the appearance of five millivolts across a sensing resistor is attained as well as separate examination of the positive and negative halves of the zero-bias current.

I. Introduction

The dependence of the dc Josephson supercurrent[1] upon temperature, magnetic field, and other factors, has been extensively studied both experimentally and theoretically since the mid 1960's. In most earlier work, the critical current as a function of either magnetic field or temperature has been probed with point-by-point plotting. The tedious nature of this measurement has prompted the development of a number of techniques for the automatic recording of this measurement.

Several early workers[2-4] have employed methods utilizing a phase sensitive detector sensing the amplified voltage across the junction in order to determine the relative time the junction spends at zero bias. The changes in the dc output of the lock-in correspond to a signal proportional to the dc Josephson current, provided that current exceeds some minimum value (typically 100μA). Below this level, direct proportionality is lost.

Another work[5] described an electro-mechanical system producing an oscillating voltage whose envelope followed the behavior of the Josephson current as a function of magnetic field.

Finally, a later paper[6] outlined a technique for oscilloscope observation of the variations in the supercurrent which had the limitations of only displaying the positive side of the critical current, and requiring a fairly large (1 mv) voltage step to produce the pulses required by the technique.

In the present work, we outline a technique that has the advantages of being fully self-contained (no phase detectors or external amplifiers needed), providing separate positive, negative, and total critical current outputs, and having high sensitivity. Critical currents of sub-microamp amplitude and switching voltages on the order of ten microvolts are within the capabilities of the apparatus constructed.

We describe below the basic operations of this circuit, as well as the details of its design.

II. Outline of the Technique

Figure 1a shows the current-voltage characteristic of a Josephson junction with the sequence of voltage switching transitions indicated by the sequence of letters. The quantity to be measured is the total amplitude of the zero-bias current. The sudden appearance of a voltage at the transitions A-B and D-E in the figure serves as the triggering impulse for the measurement circuit. Since the junction undergoes hysteretic behavior, it is necessary for the circuit to logically distinguish the voltage-on transitions from the voltage-off transitions. The speed of the transitions and the characteristic voltages require a circuit capable of wide bandwidth and differential sensitivity to microvolt signals. These requirements are met in the following manner.

Referring to figure 2, a current source provides a variable amplitude triangle wave to the junction. The junction current is sensed by R_{sense} and amplified by the junction current amplifier; it is then precision rectified into positive and negative half cycles.

The voltage pulse amplifier converts the switching characteristic into the stairstep waveform shown in figure 1b and indexed to the same letter sequence as in figure 1a. Distinguishing the zero-to-positive and zero-to-negative voltage transitions from the rest of the waveform is accomplished by the pulse forming network, which also converts the resulting pulses into the proper form to drive the sample-and-hold circuits.

The sample-and-hold circuits sample the junction current for 100 microseconds from the moment of the transition and make available dc signals proportional to the positive and negative critical currents. The summing amplifier then provides an algebraic sum of the two signals as the final output of the circuit.

III. Circuit Details

The junction current amplifier is realized in the form of a unity gain differential amplifier (U1 in figure 3) which senses the voltage developed across R_{sense} by the actual junction current. The positive and negative half cycles of this signal are each rectified by precision rectifiers U2 and U3. A precision rectifier is a circuit configuration which simulates a perfect diode with no forward voltage drop. U5 serves to invert the negative half cycle in order to simplify the sample-and-hold circuitry. U4 and U5 also serve as followers, as the precision rectifier's high output resistance renders it incapable of supplying the current required to drive the sample-and-hold circuits Q1 and Q2.

The timing pulses that drive the sample-and-hold gates are derived as follows: the LM318 high slew rate operational amplifier is used as a super high gain differential amplifier. In this configuration, the inherent offset voltage of the operational amplifier itself presents a problem and must be nulled out by offset adjustment R_1. This assures that the output of the LM318 will return to zero when the junction voltage disappears. In practice, this adjustment is accomplished by observing the waveform present at point P in figure 2 and adjusting R_1 until the stairstep waveform of figure 1b appears. The two LM311's act as threshold detectors set at $\pm$ 2/3 the supply voltage and serve to greatly reduce the circuit's sensitivity to offset variances in the LM318 and to greatly improve overall noise immunity.

The 4049BE and 4001BE CMOS packages act to invert polarity where required and also act as 100 microsecond one-shot pulse generators to drive the sample-and-hold gates. The one-shots are sensitive to rising edges only, so as to respond only to the proper transitions.

When the gates each fire, their associated holding capacitors C1 and C2 are charged to a voltage corresponding to the junction current at the point of the junction's voltage switching transition of the appropriate polarity. These capacitors are followed by extremely high input resistance followers (LM310's) in order to minimize drift; the signals are then summed in U7, which also acts as a low-pass filter, thereby providing smoother operation of a chart recorder. A ±15 volt supply -- heavily bypassed at each integrated circuit -- powers the circuit.

III. Applications

Operation of this device is particularly simple since it is self-contained. For our experiments, current sources for both the junction and for a superconducting solenoid have been built into the device. In this form, we have dubbed the device the "SLAMJAM" (Simon-Landmeier Automated Josephson Ammeter).

For magnetic field measurements, standard four-probe connections are made to the junction and leads from the junction and for the field current are taken from the probe via a hermetically sealed multipin connector. Magnetic shielding is accomplished with a mu-metal can surrounding the sample and magnet. The current and voltage leads are connected directly to the SLAMJAM. To record magnetic field dependencies, the output of the circuit is fed to the y axis of an xy recorder, while a voltage proportional to the magnet drive current feeds the x axis. Depending upon the noise characteristics of the junction at hand, a field sweep of fifty gauss (5×10^{-3} Tesla) can be made within a couple of minutes.

Errors introduced by the device are directly proportional to the frequency of the junction current driver and inversely proportional to the fraction of the maximum current that is to be resolved in the measurement. With the present pulse circuitry, a sweep rate below 25HZ is suitable to avoid significant errors. For still finer resolution, the sample-and-hold gates could be driven by pulse-generators faster than the 100 microsecond type utilized here.

A magnetic field plot is shown in figure 4, which is from a tin/tin oxide/lead sample. Both films were of 3000Å thickness; the tin film was 0.25 mm wide, the lead film 0.5 mm wide. The room temperature resistance of the junction was 0.2Ω. As is often the case, the current minima are not all identically zero due to nonuniformities in the oxide layer. We have also noted some junctions in which the positive and negative parts of the critical current were not equal, thus prompting the inclusion of facilities to observe the two parts separately in this circuit.

The circuit is applicable to the measurement of the temperature dependence of the Josephson current and it has also been suggested that critical currents in superconductors can be measured by this technique.

There are a number of refinements to the circuitry presented here that have recently become technologically feasible which promise substantial improvements in current sensitivity and sampling speed if such capabilities become useful.

IV. Acknowledgements

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References

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Captions for Figures

Figure 1a: "Josephson Junction Current-Voltage Characteristic"

Figure 1b: "Output of Voltage Pulse Amplifier"

"(lettered points correspond to those on figure 1a)"

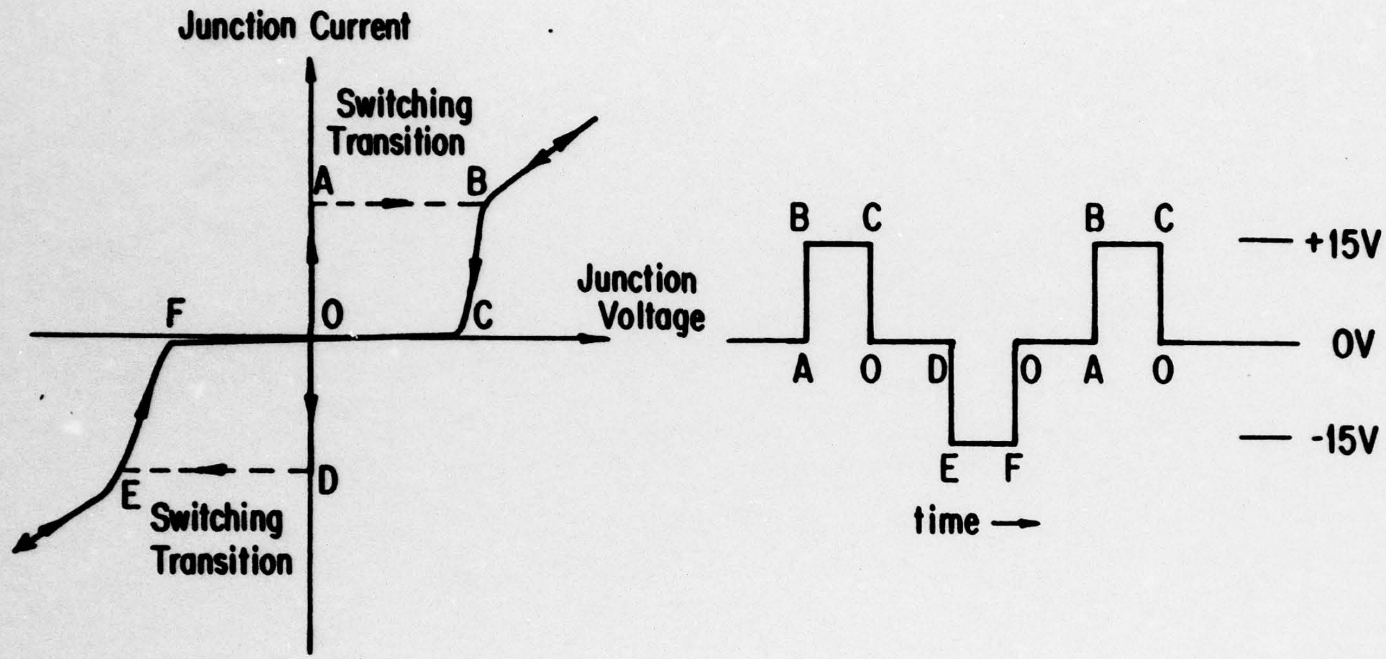
Figure 2: "Block Diagram"

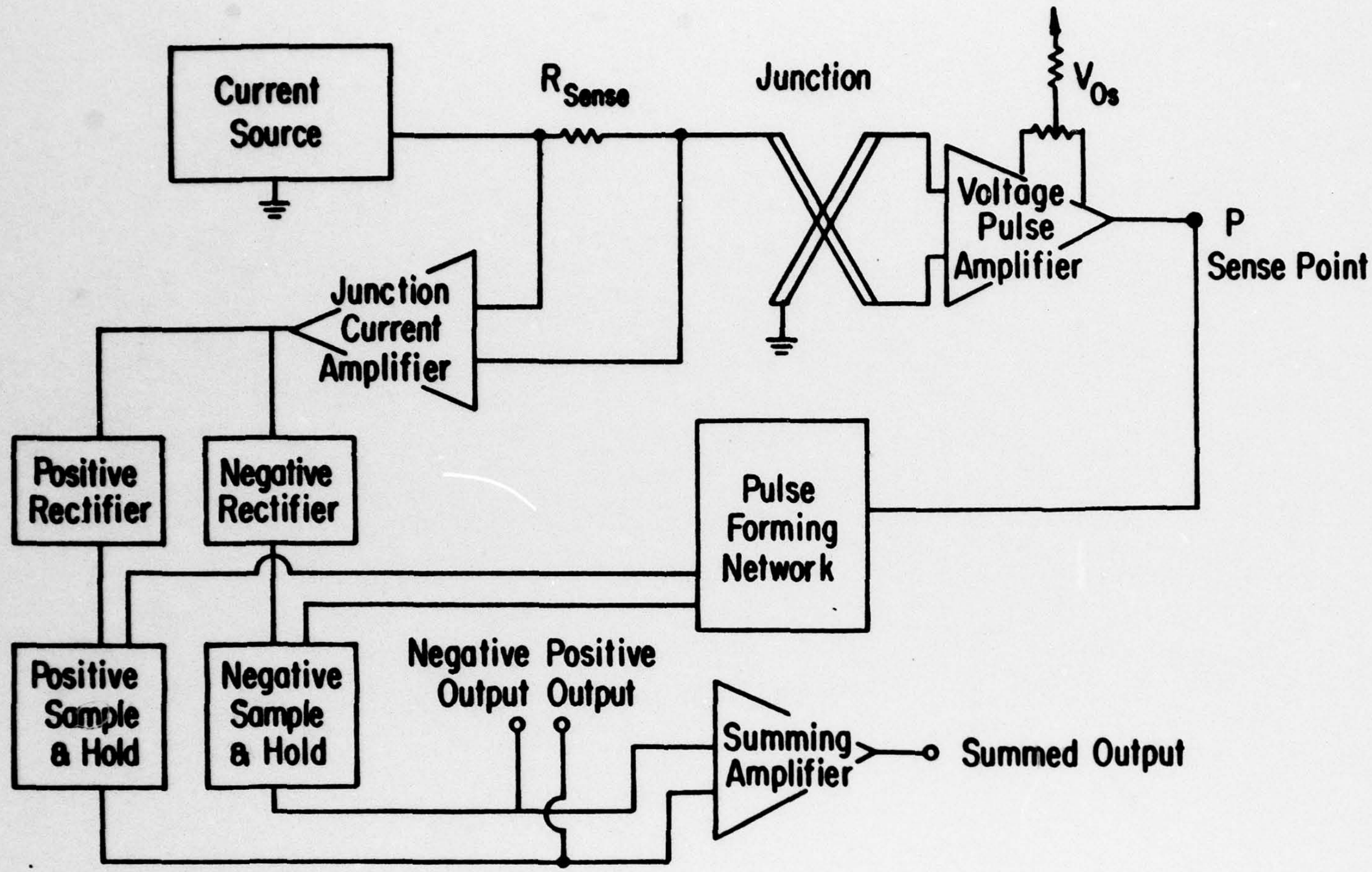
Figure 3: "Circuit Diagram"

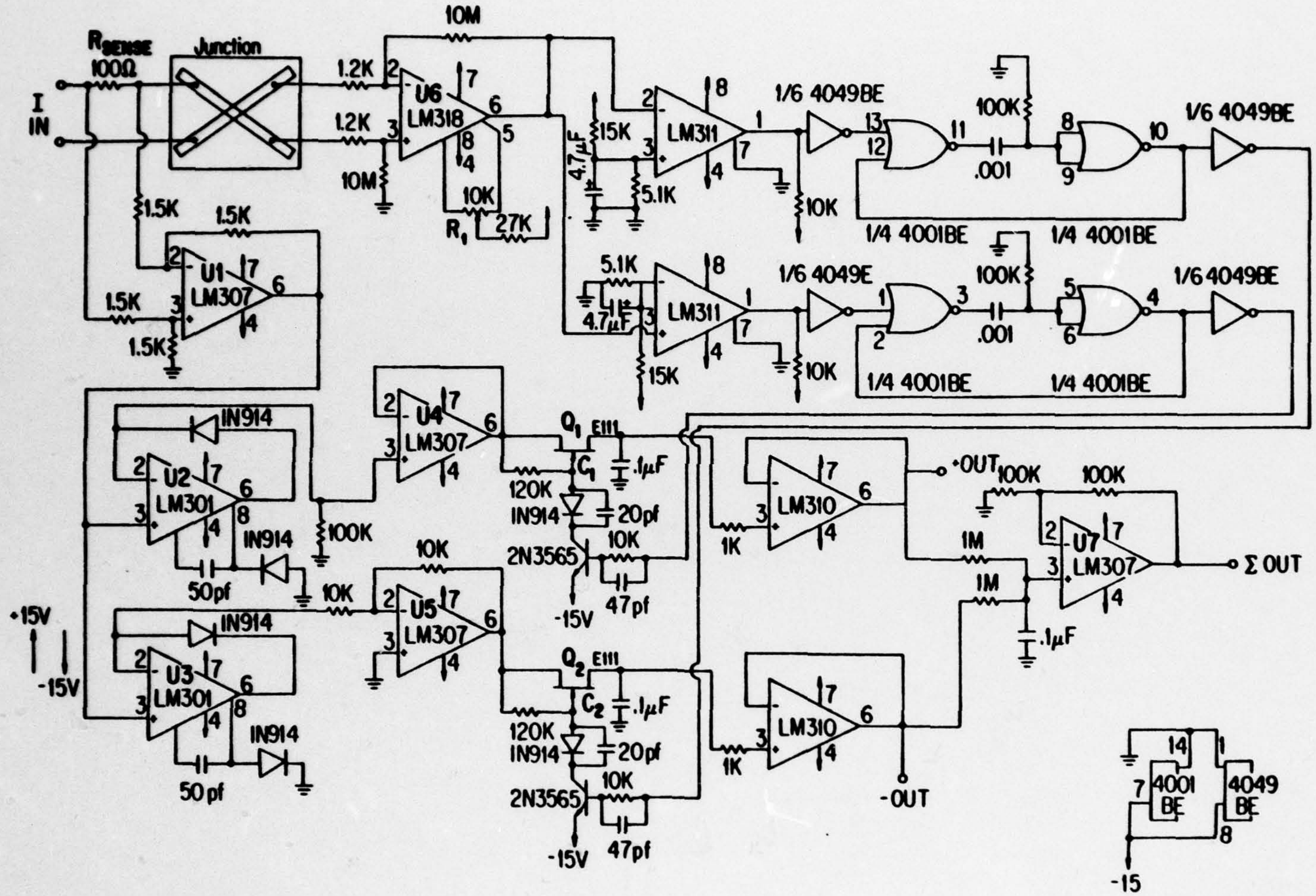
"Generous supply bypassing is required in this circuit consisting of 0.1 μf capacitors on supply pins of each I.C."

"All resistors 1/4 watt 5%"

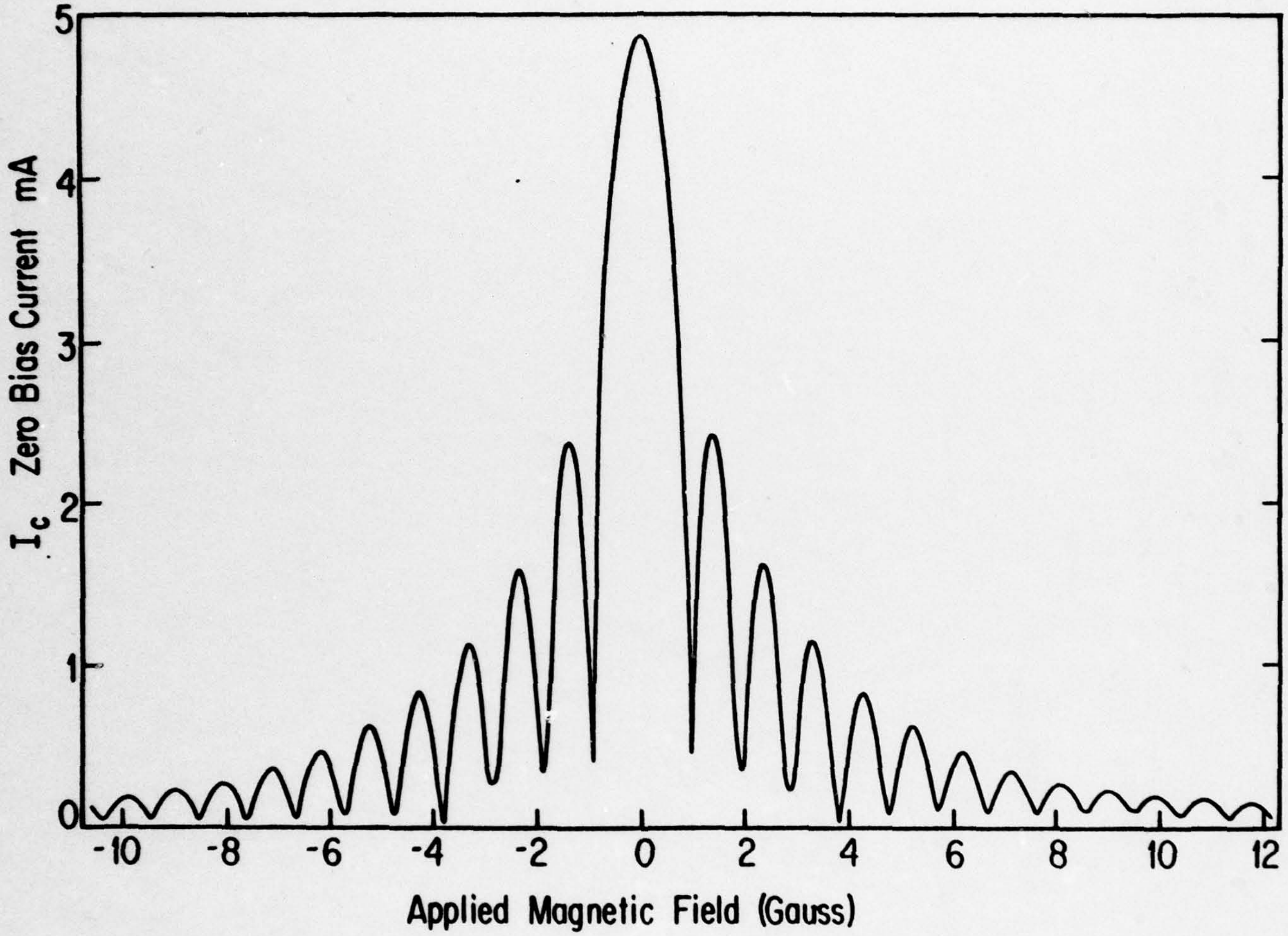
Figure 4: "Magnetic Field Dependence of a Tin/Lead Josephson Junction"


Junction Current
Switching Transition
A
B
O
C
F
Junction Voltage
D
E
Switching Transition
B C B C
+15V
0V
A O D O A O
-15V
E F
time


Current Source
R_{Sense}
Junction
V_{Os}
Voltage Pulse Amplifier
P
Sense Point
Junction Current Amplifier
Positive Rectifier
Negative Rectifier
Pulse Forming Network
Positive Sample & Hold
Negative Sample & Hold
Negative Output
Positive Output
Summing Amplifier
Summed Output



I IN
R SENSE 100Ω
Junction
1.2K
1.2K
10M
10M
U6 LM318
10K
27K
R1
1.5K
1.5K
1.5K
1.5K
U1 LM307
15K
5.1K
4.7μF
LM311
LM311
1/6 4049BE
1/6 4049E
1/4 4001BE
.001
100K
10K
U2 LM301
U3 LM301
IN914
50pf
100K
10K
U4 LM307
U5 LM307
Q1 E111
Q2 E111
C1
C2
.1μF
120K
20pf
2N3565
47pf
-15V
+15V
LM310
1K
+OUT
-OUT
1M
U7 LM307
Σ OUT
4001 BE
4049 BE
-15


I_c Zero Bias Current mA
0
1
2
3
4
5
-10
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-4
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8
10
12
Applied Magnetic Field (Gauss)